LUNAR ACCRETION AFTER A HIGH-ENERGY, HIGH-ANGULAR MOMENTUM GIANT IMPACT.
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Introduction. In the giant impact hypothesis for lunar origin [1, 2], the Moon accretes from a hot circumterrestrial disk. The lunar accretion disk is typically modeled in a manner similar to astrophysical planet-forming disks [3]. In the canonical model [4], the giant impact prescribes the present-day angular momentum (AM) of the Earth-Moon system and emplaces partially vaporized material into orbit.

In current models of lunar accretion [5], material outside the Roche limit, where a satellite can withstand tidal breakup (~$3R_{Earth}$), condenses and accretes quickly to form a lunar seed. Viscous spreading of the Roche-interior disk delivers some disk material to Earth and generates new moonlets beyond the Roche limit that are quickly accreted onto the lunar seed. In most models, the Roche-interior disk evolves with an assumed energy balance between radiative cooling and viscous heating [6]. However, Charnoz & Michaut [7] found that this energy balance is never attained and cooling dominates. The full implications of their result on lunar accretion models have not yet been quantified.

The complexity of lunar accretion currently precludes a robust treatment of both the physical assembly and chemical composition of the growing Moon. Estimates of the depletion of moderately volatile elements due to incomplete condensation in the lunar disk [8] do not quantitatively reproduce the observed depletion pattern in the Moon [9]. Finally, the striking isotopic similarity between Earth and the Moon is not yet explained by the canonical model [10].

High-Energy, High-Angular Momentum Giant Impacts. In 2012, a new class of giant impacts was proposed for lunar origin [11, 12]. Originally motivated by the isotopic similarity between Earth and the Moon, these studies proposed specific impact scenarios that could generate lunar disks composed of the same ratio of material from the two impacting bodies as emplaced in the terrestrial mantle. However, to achieve the desired level of mixing, the post-impact system had a higher AM than the present day. Thus, a subsequent process is required to transfer AM away from the system after lunar accretion to reach the present-day conditions. Multiple possible AM transfer processes have been proposed [11, 13-15].

Impact events with higher energy and AM than the canonical case can generate a new type of planetary structure [16, 17], which was not recognized in 2012 or in the first models of lunar accretion with high AM [18]. This structure, which is continuous from a corotating inner region to a disk-like outer region, was named a *synestia* by [16]. A rotating body forms a synestia when it exceeds the *corotation limit*, defined by the thermal limit where the equatorial rotational velocity intersects the Keplerian orbital velocity. The dynamics of moon formation from a synestia are different than in traditional lunar accretion disks [16, 19]. For example, the structure is dynamically continuous, net mass transport from the disk to the co-rotating region is limited, and substantial amounts of vapor can extend beyond the Roche limit.

Lock et al. [19, 20] proposed that the Moon accreted from a synestia. As moonlets formed, they chemically equilibrated with the vaporized bulk silicate Earth (BSE). Equilibration of a partial condensate with the BSE vapor at 10's of bars and at temperatures buffered by the vaporization of silica can reproduce the observed pattern of moderately volatile elements in the Moon [19, 21]. Rapid mixing within the synestia can explain the observed isotopic similarity [16, 19, 20] and free the high-energy, high-AM impact hypothesis from requiring tuned impact conditions.

Lock et al. [19, 20] presented a calculation of radiative cooling of an impact-generated synestia that tracked the pressure field and the mass and AM of Roche-exterior condensates. They found that the Moon accreted within the BSE vapor. However, their work did not calculate the *N*-body accretion of the moonlets or the feedback of moonlets on the vapor structure.

Lunar Accretion within a Synestia. Here, we investigate the process of lunar accretion after a high-energy, high-AM giant impact. Initially, beyond the Roche limit, the vapor pressure is 10's of bars and there is an initial debris field of partial condensates. The mass and AM of the Roche-exterior condensate and vapor depends on the specific impact scenario.

At present, no single numerical method can capture the complete physics of the subsequent evolution of the structure and lunar accretion. We employ two different methods to investigate aspects of the problem.

Using the GADGET-2 smoothed particle hydrodynamics (SPH) code [22, 23], we model radiative cooling of the synestia without accounting for the presence of the growing Moon. Because SPH time steps are determined by the sound speed, radiative cooling is approximated by using an artificially large photospheric temperature. Then, simulation time is scaled to an equivalent cooling time. Condensing mass with sufficient AM to remain beyond the Roche limit is removed from the SPH calculation. Mass that condenses within the Roche limit re-vaporizes, and the vapor mass is added back into the structure. The vapor structure shrinks over time, eventually receding to within the orbit of the Moon. We estimate that the Moon separates from the vapor structure after 10's of years [19]. We will determine the evolution of the vapor pressure in the synestia to derive a time-dependent gas drag function and the range of pressures for chemical equilibration between moonlets and the vapor.

Material ejected into orbit at large radii quickly condenses and accretes to form an initial set of moonlets and the primary lunar seed. The initial orbit of the lunar seed lies within the synestia. We use SPH to model the perturbation of the synestia's pressure field by the lunar seed and moonlets. Fig. 1 presents an example SPH calculation. The colors denote the gravitationally-equilibrated density of an impact-generated synestia immediately after an impact event and before any cooling. In this example, we have inserted a lunar mass satellite to illustrate the spatial scales of the Moon and the perturbation to the synestia.

Due to radial pressure support, the vapor in a synestia has a sub-Keplerian orbit. Embedded moonlets on Keplerian orbits have larger angular velocities and act like spoons that stir the vapor, aiding in mixing of the structure. The drag created by the slower moving vapor also causes the orbits of moonlets to decay.

In our SPH cooling calculations, we have assumed that accretion of Roche-exterior condensates onto the lunar seed is efficient. To test this assumption, we use the *N*-body code PKDGRAV [24, 25] to model the accretion of condensates beyond the Roche limit. We implement an oblate gravity field and gas drag corresponding to the time-varying mass distribution of the synestia. The initial particle field is based on the distribution of condensates determined from SPH impact simulations. Over time, additional particles are inserted into the simulation to approximate the formation of small moonlets by condensation. Particles that fall deep into the structure would be vaporized and are removed from the calculation. We will explore the accretion process as mass condenses in the synestia to form new moonlets in the presence of a lunar seed.

Conclusions. Lunar accretion within a synestia is a substantially different process than accretion from a traditional disk. Compared to previous models of a circumterrestrial disk [5, 18], the main stage of moon formation from a synestia would be faster, only 10's of years. We seek to determine the range of vapor pressures surrounding the growing moonlets to be able to predict their chemical composition and to test the robustness of the high-energy, high-AM giant impact hypothesis for lunar origin [19, 21].

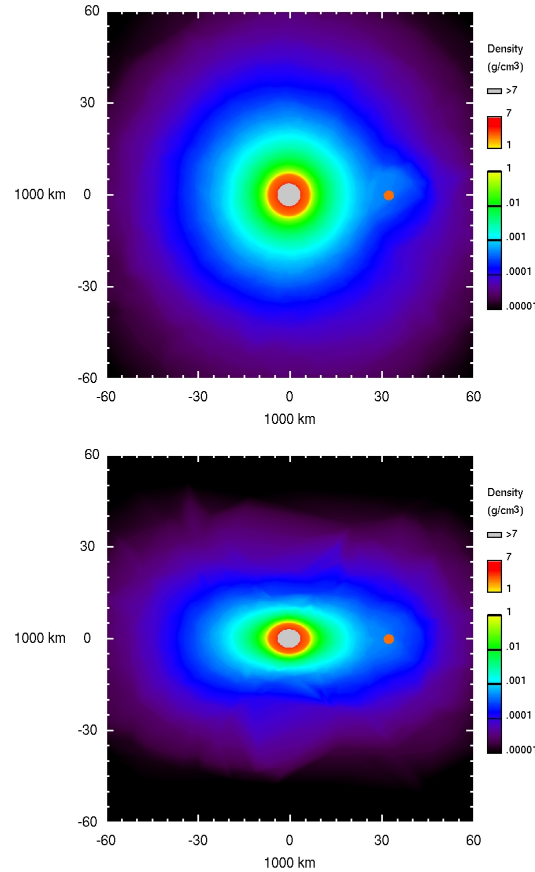

Fig. 1. Density contours in an impact-generated synestia immediately after the impact and before cooling (top – midplane; bottom – plane perpendicular to the spin axis). A lunar-mass satellite is embedded to illustrate the perturbation to the structure.

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